CHAPTER 1

THE SCALE OF THE COSMOS

We are going on a voyage out to the end of the universe. Marco Polo journeyed east, Columbus west, but we will travel away from our home on earth, out past the moon, sun, and other planets, past the stars we see in the sky, and past billions more that we cannot see without the aid of the largest telescopes. We will journey through great whirlpools of stars to the most distant galaxies visible from earth—and then we will continue on, carried only by experience and imagination—looking for the structure of the universe itself.

Besides journeying through space, we will also travel in time. We will explore the past: see the sun and planets form and search for the formation of the first stars and the origin of the universe. We will also explore forward in time to watch the sun die and the earth wither. Our imagination will become a scientific time machine to search for the ultimate end of the universe.

Though we may find an end to the universe, a time when it will cease to exist, we will not discover an edge. It is possible that our universe is infinite and extends in all directions without limit. Such vastness dwarfs our human dimensions, but not our intelligence or imagination.

Astronomy—this imagined voyage—is more than the study of stars and planets. It is the study of the universe in which we exist. Our personal lives are confined to a small corner of a small planet circling a small sun drifting through the universe, but astronomy can take us out of ourselves and thus help us understand what we are.

Our study of astronomy introduces us to sizes, distances, and times far beyond our common experience. The comparisons in this chapter are designed to help us grasp their meaning.

The longest journey begins with a single step.

Confucius

(Michael A. Seeds)

How big is a star? The answer—roughly 1 million miles in diameter—is meaningless. Such a large number tells us nothing. How can we humans, only 5 or 6 feet tall, hope to understand the vastness of the universe? The secret lies in the single word *scale*.

To understand the universe, we must understand the relative scale of planets, stars, galaxies, and the universe as a whole. Only when we can relate our own body size to the astronomical universe around us can we begin to understand nature on the grandest scale.

To illustrate the scale of astronomical bodies, to fit ourselves into the universe, we will journey from a campus scene to the limits of the cosmos in 12 steps. Each step will widen our view by a factor of 100. That is, each successive picture in this chapter will show a region of the universe that is 100 times wider than the preceding picture.

This scene shows a region about 52 feet across. It is occupied by a human being, a sidewalk, and a few trees—all objects whose size we can understand. Only 12 steps separate this scene from the universe as a whole.

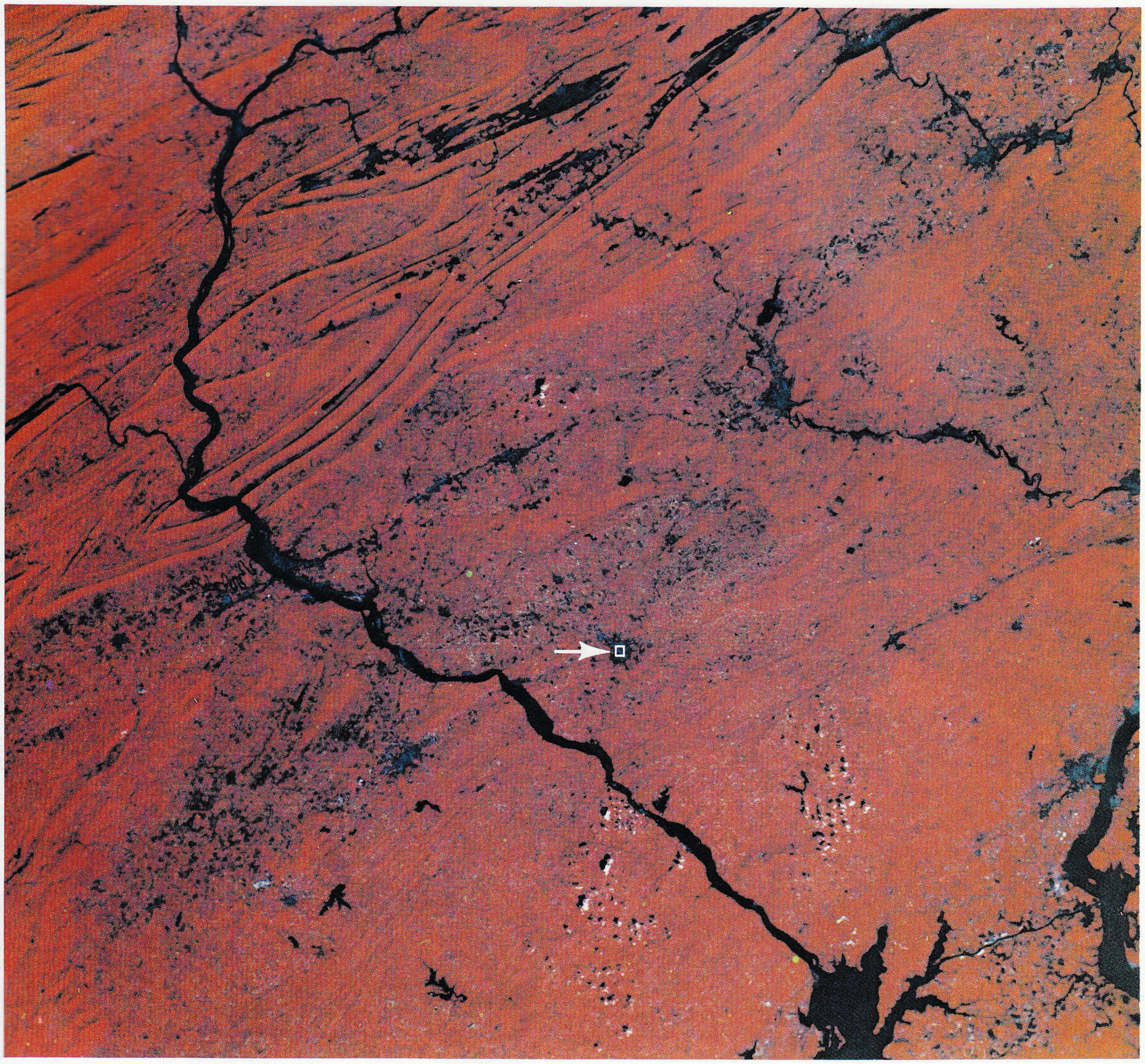
Field of view enlarged 100 times from previous image (Pennsylvania Department of Transportation, Bureau of Design)

We now increase our field of view by a factor of 100, which is an area 1 mile across. The area of the preceding photograph is shown by the small square (arrow). Individual people, trees, and sidewalks vanish, but now we can see a college campus and the surrounding streets and houses.

These dimensions are familiar. We have been in houses, crossed streets, and walked or run a mile. We have personal experience with such dimensions, and we can relate them to the scale of our bodies.

Although we have begun our adventure using feet and miles, we should use the metric system of units because it makes arithmetic simpler (Appendix C). One mile is 5280 feet and each foot 12 inches, so 1 mile is $5280 \times 12 = 63{,}360$ inches. If we use the metric system, this calculation is easier. One kilometer (km) is 1000 meters (m), and each meter is 100 centimeters (cm). Thus, 1 km is $1000 \times 100 = 100{,}000$ cm.

One mile equals 1.609 km, so our photograph is about 1.6 km across. (See Appendix C for other conversion factors.) Only 11 more steps of 100 separate us from the largest dimensions in the universe. The next photograph will span 160 km.



Field of view enlarged 100 times from previous image (NASA infrared photograph)

Our field of view now spans 160 km, about 100 miles. The college campus is invisible, and we see only a few signs of human activity. Cities are visible as dark blotches, and farm lands are visible as tiny rectangular shapes. The suburbs of Philadelphia are visible at the lower right. Green foliage appears red in this infrared photo.

At this scale we see the natural features of the earth's surface. The Allegheny Mountains of southern Pennsylvania cross the photograph in the upper left, and the Susquehanna River flows southeast into the Chesapeake Bay. A few puffs of clouds dot the area.

These features remind us that we live on the surface of an evolving planet. Forces in the earth's crust pushed the mountain ranges up into parallel folds, like a rug wrinkled on a polished floor. The clouds remind us that the earth's atmosphere is rich in water, which falls as rain and erodes the mountains, washing material down the rivers and into the sea. The mountains and valleys that we know are only temporary features; they are constantly changing.

As we explore the universe, we will see that it, like the earth's surface, is evolving. Change is the norm in our universe. We will see stars evolving and dying. And we will discuss the possible end of the universe.

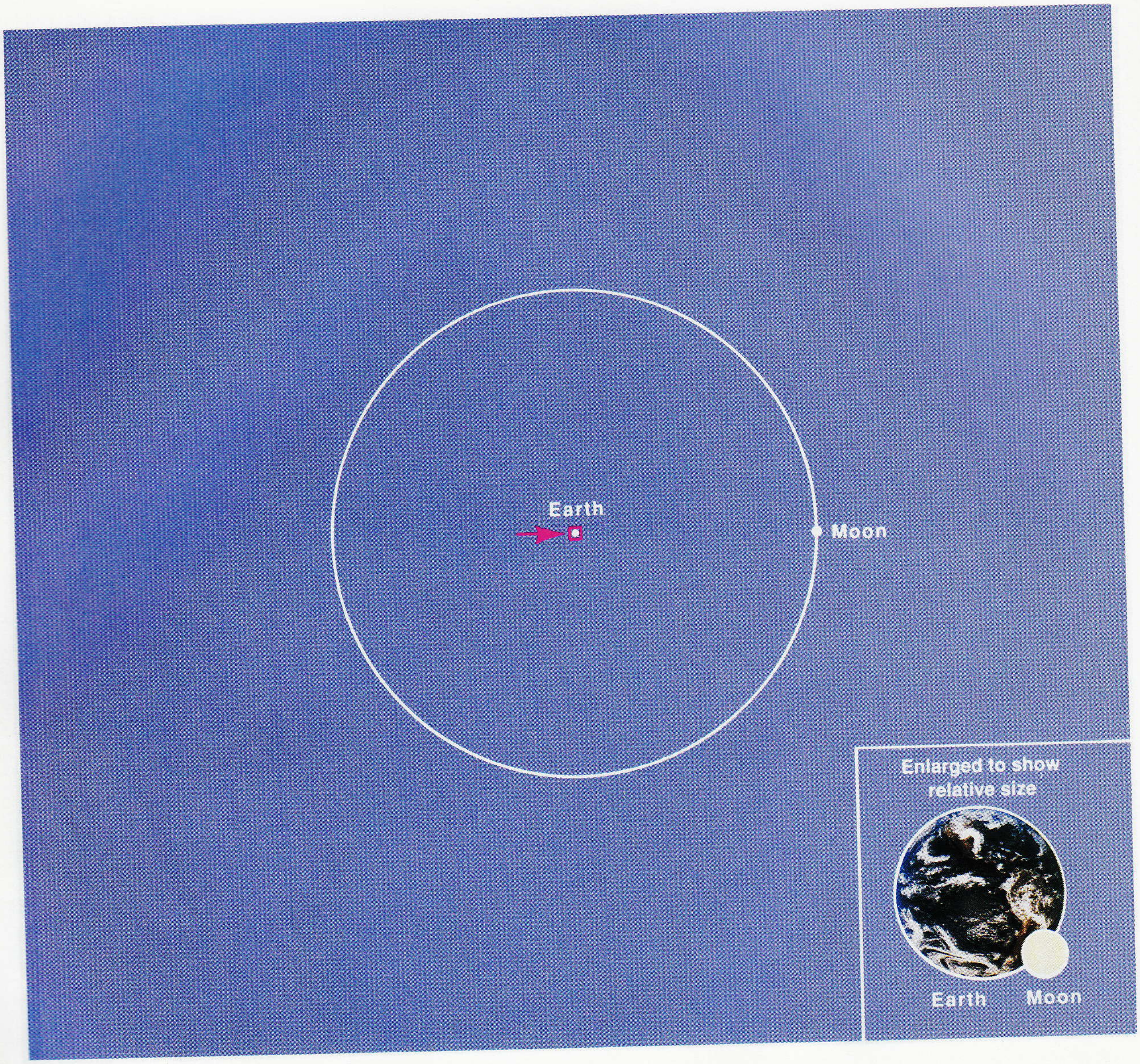
Field of view enlarged 100 times from previous image (NASA)

The next step in our journey shows our entire planet. The earth is 12,756 km in diameter and rotates on its axis once a day.

This image shows most of the daylight side of the planet, with the sunset line at the extreme right. The rotation of the earth carries us eastward across the daylight side, and, as we cross the sunset line into darkness, we say the sun has set. Thus, the rotation of our planet causes the cycle of day and night.

We know that the earth's interior is made of iron and nickel and that its crust is mostly silicate rocks. Only a thin layer of water makes up the oceans, and the atmosphere is only a few miles deep. On the scale of this photograph, the depth of the atmosphere on which our lives depend is less than the thickness of a piece of thread.

The water and air on our planet has made life possible, but we know of no other planet where such conditions exist. Only eight other planets orbit the sun in our solar system, and none have liquid water on their surfaces. In addition, we can see no other planets orbiting other stars. Such planets probably exist, but they are too distant to detect. So far as we know, we are the only life in the universe.



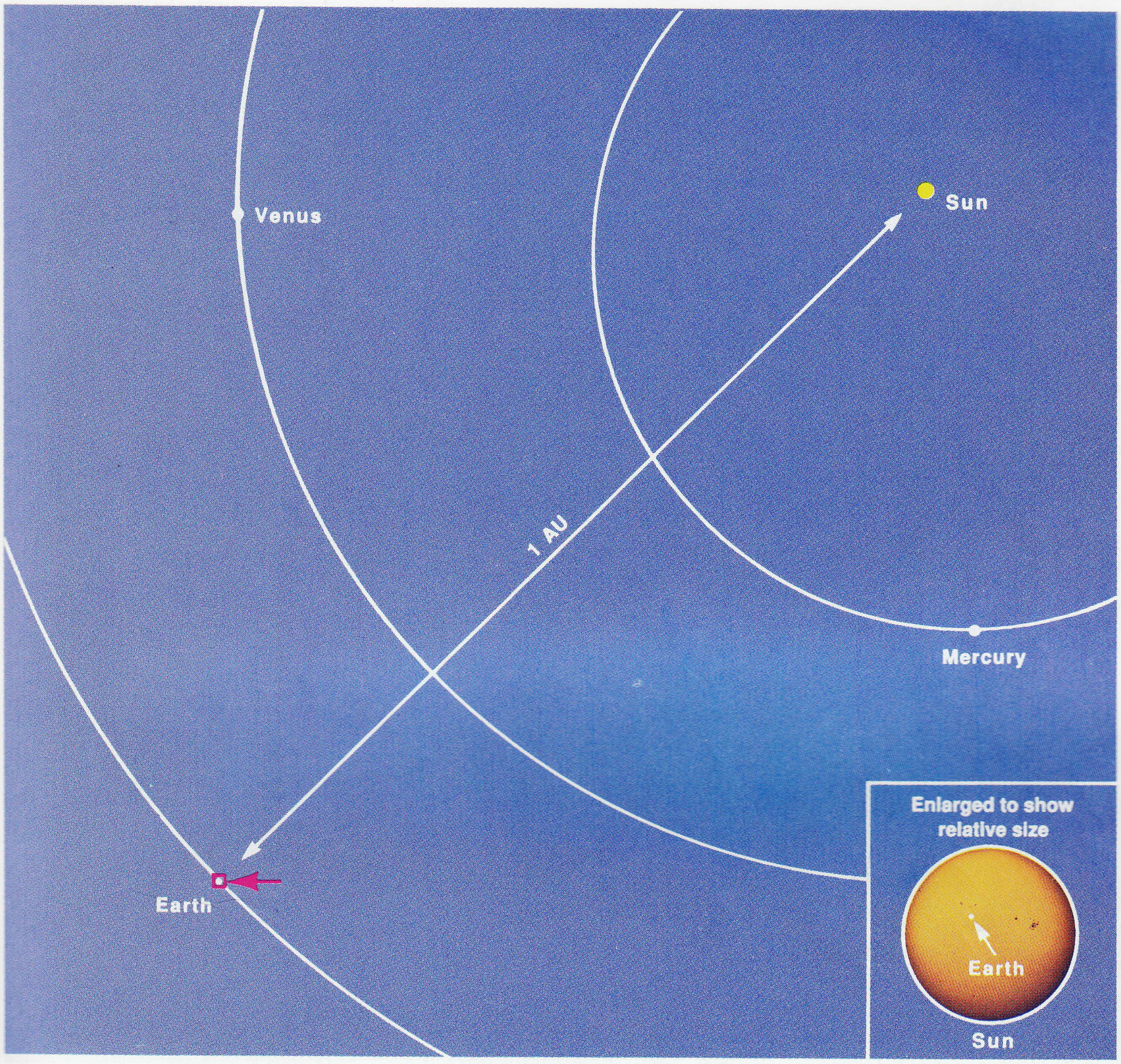
Field of view enlarged 100 times from previous image

Again we enlarge our field of view by a factor of 100, and we see a region of the universe 1,600,000 km wide. Earth is the small white dot in the center, and the moon, only one-fourth its diameter, is an even smaller dot along its orbit 380,000 km from the earth.

These numbers are so large that it is inconvenient to write them out. Astronomy is the science of big numbers, and we will use numbers much larger than these to discuss the depths of the universe. Rather than write these numbers out, it is convenient to write them in **scientific notation.** It is nothing more than a simple way to write big numbers without writing a great many zeros.

In scientific notation we would write 380,000 as 3.8×10^5. The 5 tells us to move the decimal point five places to the right. The 3.8 then becomes 380,000. In the same way, we would write 1,600,000 as 1.6×10^6. Notice that we could also write this as 16×10^5 or 0.16×10^7. It is the same quantity.

We can also use scientific notation to write very small numbers. If you are not familiar with scientific notation, consult Appendix C. The universe is too big to discuss without using scientific notation.



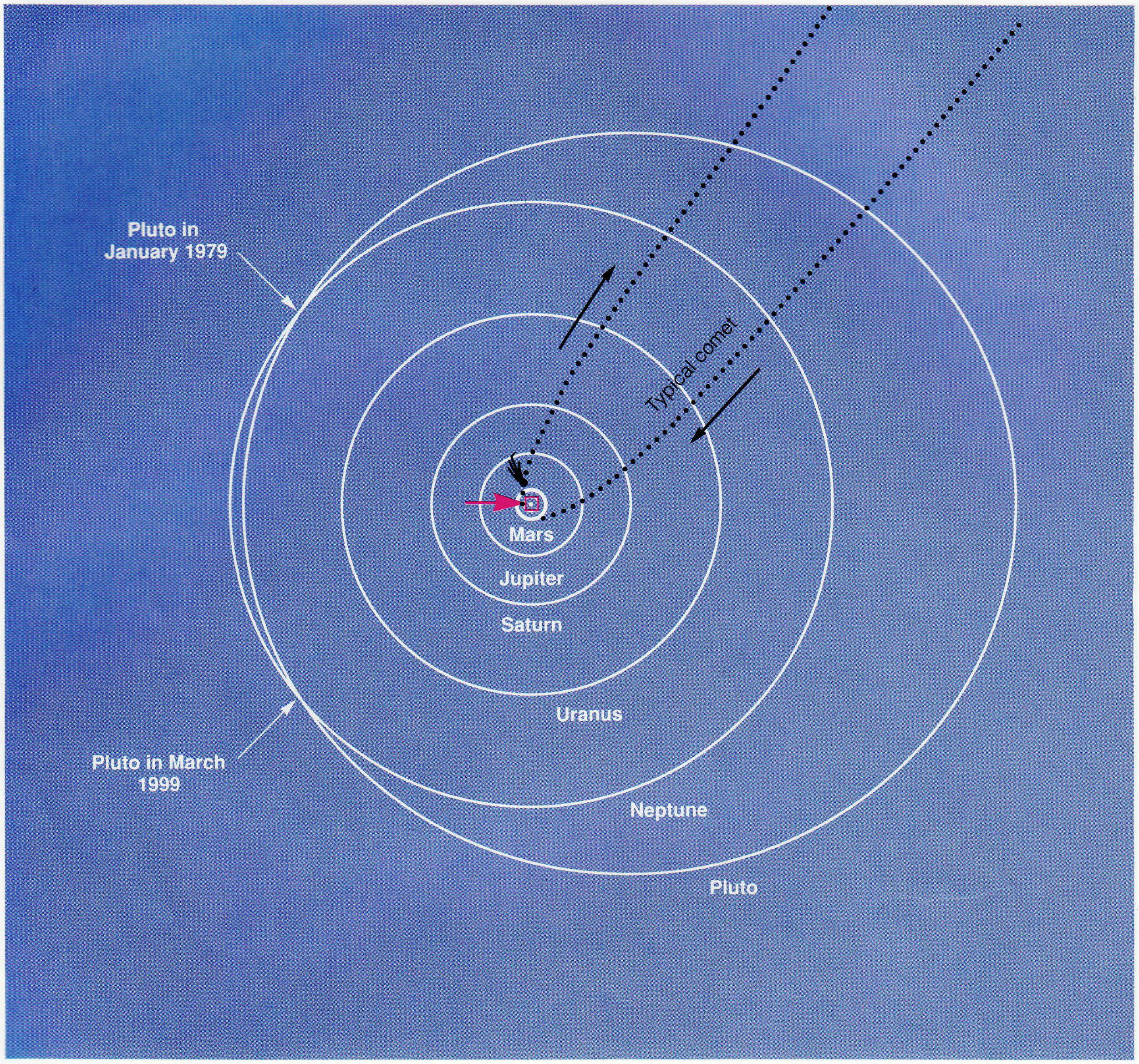
Field of view enlarged 100 times from previous image

When we once again enlarge our field of view by a factor of 100, Earth, the moon, and the moon's orbit all lie in the small red box at lower left. But now we see the sun and two other planets.

Venus is about the size of Earth, and Mercury is a bit larger than the moon. On this diagram, they are both too small to show as anything but tiny dots. The sun is 109 times larger in diameter than Earth (inset), but it too is nothing more than a dot on this diagram.

This figure spans 1.6×10^8 km. One way to deal with such large distances is to define new units. Astronomers use the average distance from Earth to the sun as a unit of distance called the **astronomical unit** (AU). Using this unit we can say that the average distance from Venus to the sun is about 0.7 AU. The average distance from Mercury to the sun is about 0.39 AU.

The orbits of the planets are not perfect circles, and this is particularly apparent for Mercury. Its orbit carries it as close to the sun as 0.307 AU and as far away as 0.467 AU. Earth's orbit is more circular, and its distance from the sun varies by only 1.7 percent.



Field of view enlarged 100 times from previous image

When we began our journey, our field of view was only 52 feet (about 16 m) in width. After only six steps of enlarging our field of view by a factor of 100 at each step, we now see the entire solar system. Our field of view is 1 trillion (10^{12}) times wider than in our first view.

The details of the preceding figure are now lost in the tiny square at the center of this diagram. The sun, Mercury, Venus, and Earth lie so close together that we cannot separate them at this scale. Mars, the next outward planet, lies only 1.5 AU from the sun.

In contrast, the outer planets Jupiter, Saturn, Uranus, Neptune, and Pluto are so far from the sun that they are easy to place in this diagram. These are cold worlds far from the sun's warmth. Light from the sun takes over 4 hours to reach Neptune, which is slightly over 30 AU distant. In contrast, sunlight reaches Earth in only 8 minutes.

Notice that Pluto's orbit is so elliptical that it can come closer to the sun than Neptune. In fact, Neptune is now farther from the sun than Pluto and will remain the most distant planet in our solar system till nearly the end of this century.